

Prospect of Hadron Spectroscopy at LHCb

Ivan Polyakov

Syracuse University

Introduction

- LHCb Upgrade program and general prospects already covered by Sheldon Stone

(oversimplified) resume on detector:

- LHCb Upgrade – x10 increase of statistics wrt to now,
- LHCb Upgrade II – x50 increase of statistics wrt to now,
- Assume roughly same detector performance as in Run1&2

- Outline:

- Conventional spectroscopy
- Known exotic states (tetra- & penta-quarks)
- New tetraquarks
- New frontiers in multiquarks
- Conventional double-heavy baryons

Disclaimer:

- all numbers are very crude estimations and should be taken with skepticism
- not complete review, but rather a set of few highlight thoughts

Known states

improving knowledge

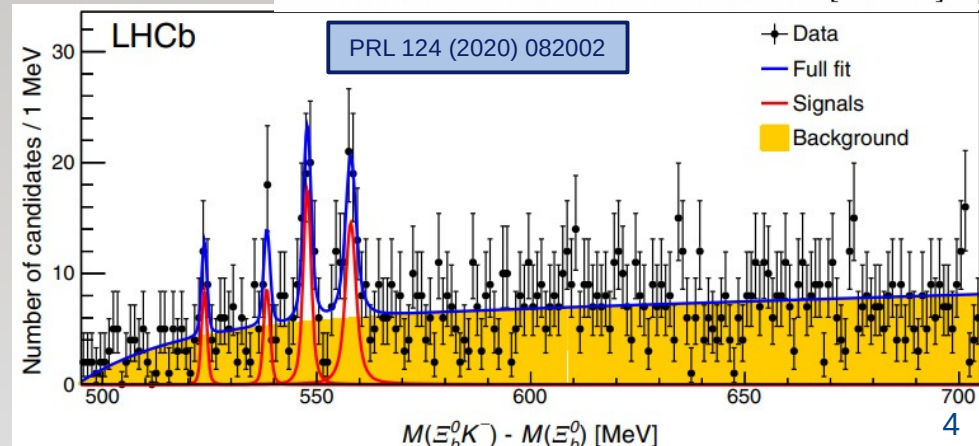
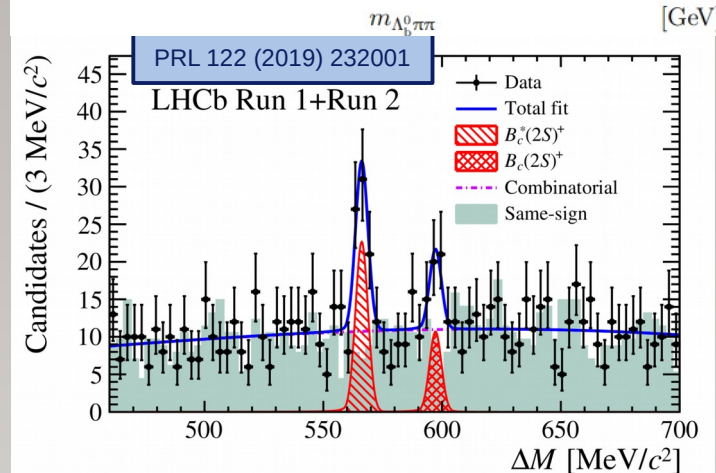
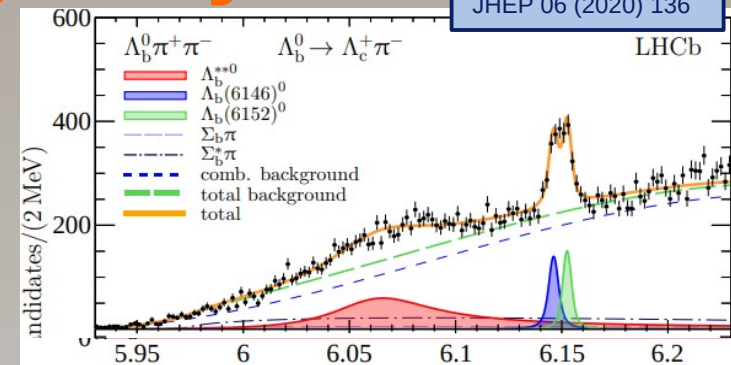
Conventional Heavy baryons

- See recent observations of excited $\Omega_{b/c}$, Λ_b , $B_c(2S)$ in $H_b + h(h')$ final states where H_b stands for b -hadron and $h(h')$ for light hadron

... and two more coming in few weeks

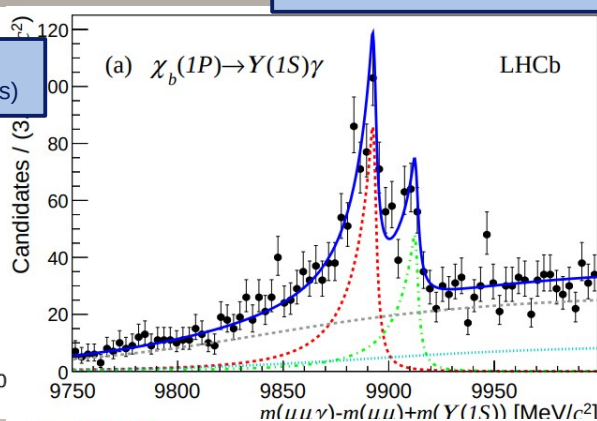
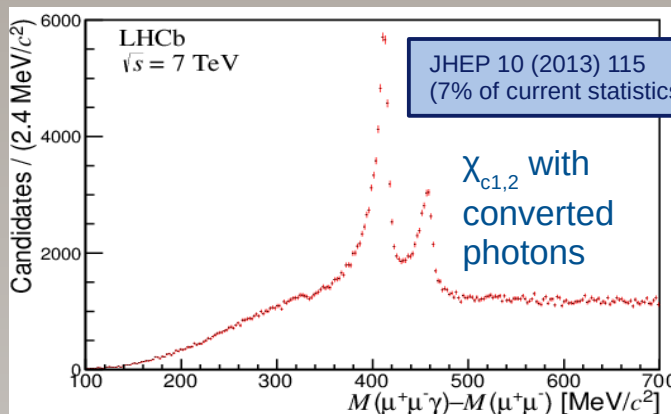
- On the edge of available statistics

- A lot more excited b/c -baryon states and decay modes to discover



Conventional quarkonium

JHEP 10 (2014) 088
(20% of current statistics)

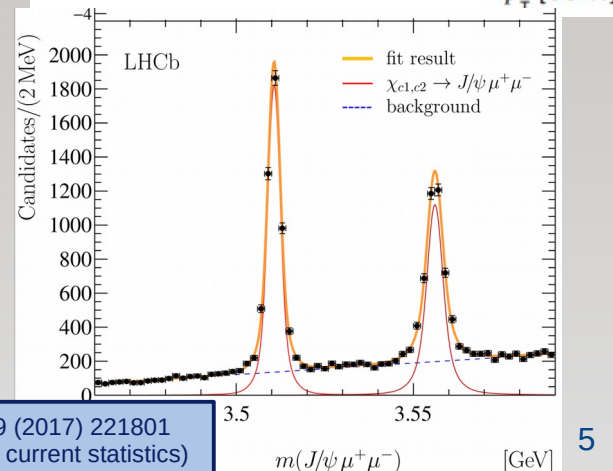
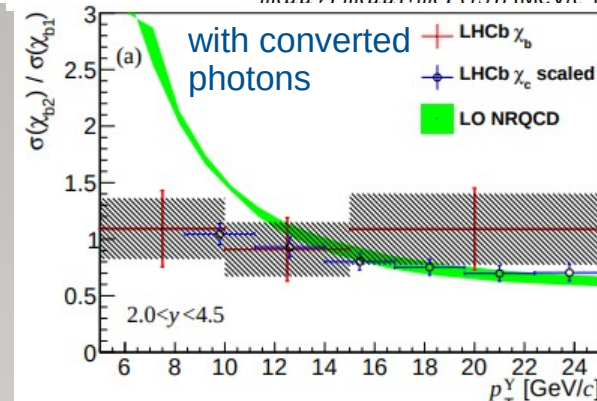


- Usage of converted photons or muon pairs to access $1P \rightarrow 1S$ transitions (with energy levels $\sim 400 \text{ MeV}$ apart)

- $O(1\%)$ suppression wrt calorimeter photon in both cases

- Access production ratios & mass splitting (width?):
 $\chi_{b0,1,2}(mP) \rightarrow Y(nS)\gamma$, $\chi_{c0,1,2}(mP) \rightarrow J/\psi\gamma$

- New states: $B_c(1P) \rightarrow B_c\gamma$,
 $H_{bJ}^* \rightarrow H_b\gamma$ where H_b is any b-hadron



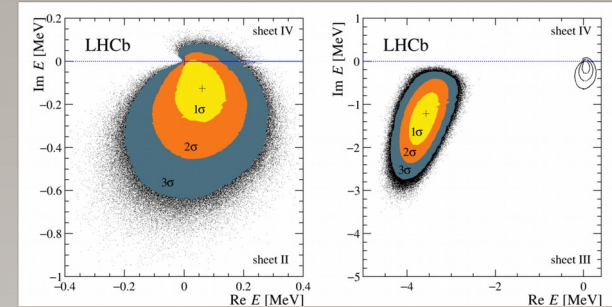
PRL 119 (2017) 221801
(50% of current statistics)

Known exotics, $X(3872)$

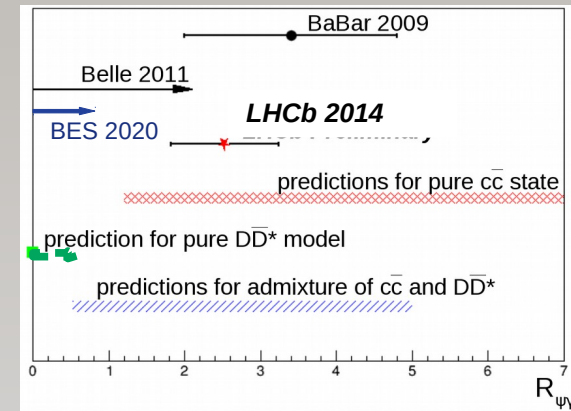
- $X(3872)$ (also known as $\chi_{c1}(3872)$) discovered by Belle in $B \rightarrow J/\psi \pi \pi K$ is the best investigated exotic state
- Recent study of $X(3872) \rightarrow J/\psi \pi \pi$ mass shape with account for $D\bar{D}^*$ threshold. Accessing pole position. First width measurement: $1.39 \pm 0.24 \pm 0.10$ MeV

Still enough questions to answer:

LHCb-PAPER-2020-008



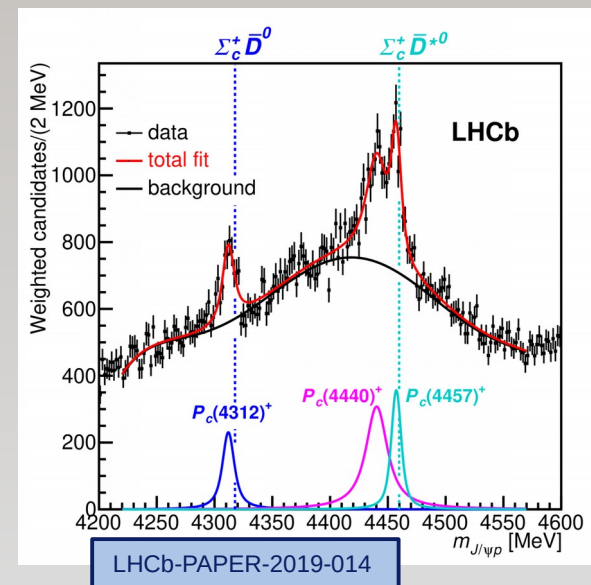
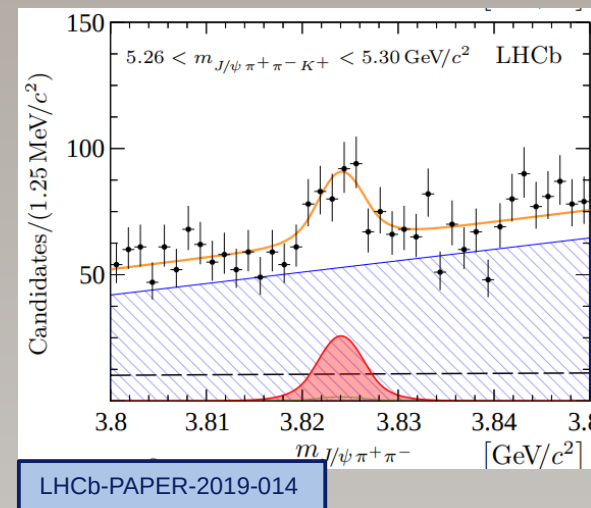
- Tension in $BR(X(3872) \rightarrow \psi(2S)\gamma)/BR(X(3872) \rightarrow J/\psi\gamma)$ between LHCb&BaBar ($\sim 2.5 \pm 0.7$) and Belle (< 2.1) & BES (< 0.6)
after upgrade should be able to probe the ratio with 0.1 precision



- Simultaneous analysis in all coupled channels: $D\bar{D}^*$, $J/\psi \pi \pi$, $J/\psi \pi \pi \pi^0$
- Does decay to $\chi_{c1}[\rightarrow J/\psi \gamma] \pi \pi$? Low reconstruction efficiency due to photon and soft pions.
hope for $O(100)$ events after upgrade(s).
- Other exotics decaying to $X(3872)+h$

Known exotics, narrow

- $X(3872)$ was observed via 1D fit of $J/\psi\pi\pi$ in $B \rightarrow J/\psi\pi\pi K$
 - x100 higher statistics
(wrt that of $X(3872)$ at the time of discovery)
allowed LHCb to observe a $\psi_2(3824) \rightarrow J/\psi\pi\pi$ nearby
 - x10 increase of statistics in $\Lambda_b \rightarrow J/\psi p K$ (Run1 \rightarrow Run1&2)
allowed to resolve $P_c(4440)$ and $P_c(4457)$
and discover $P_c(4312)$
 - How much more narrow states with hidden charmonium are there?
at least two $Z(3900)$ and $Z(4020)$ were claimed by BES-III
- What about other decay modes?
- What does proximity to Open-Charms thresholds mean?
Thorough experimental investigation needed to understand the nature



Known exotics, wide

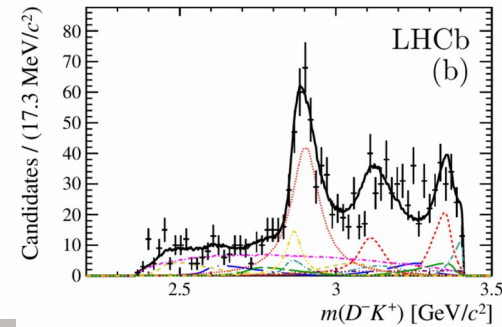
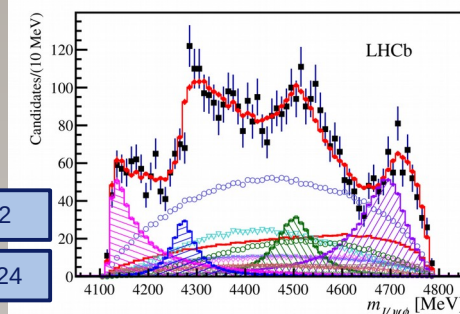
- Number of wide states have been discovered or well established in b-decays with amplitude analysis as essential tool:

- $X(4140)$ + partners in $B \rightarrow J/\psi \phi K$
- Z_c in $B^0 \rightarrow J/\psi \pi K$
- Z_c in $B^0 \rightarrow \eta_c \pi K$
- P_c in $\Lambda_b \rightarrow J/\psi p K$
- $[csud]$ as $[D^- K^+]$ in $B^+ \rightarrow D^+ D^- K^+$

PRD 95 (2017) 012002

LHCb-PAPER-2020-024

- Charmonium and light-quark spectroscopy benefits too

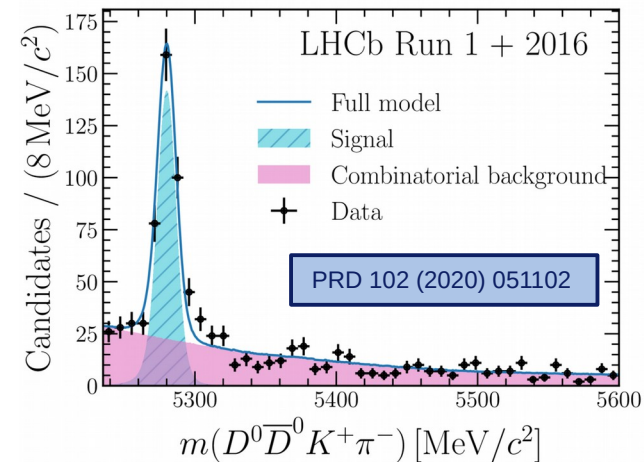
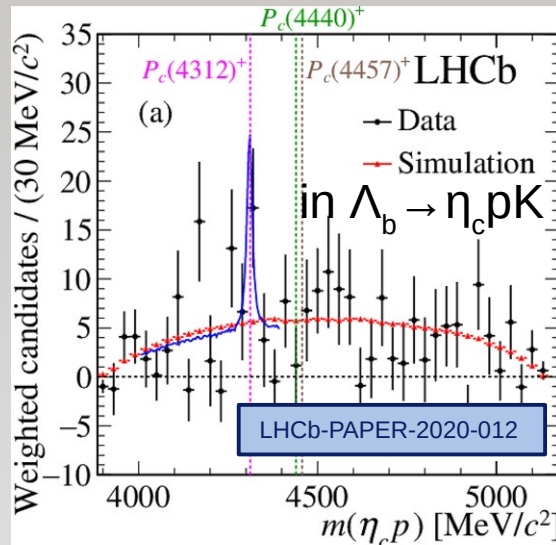


- A number of new decay modes of $B \rightarrow J/\psi + hh..$ or $B \rightarrow \bar{C}\bar{C} + hh..$ types has been observed by LHCb with statistics of $O(100)$ events:

- | | |
|---|--|
| - $\Lambda_b \rightarrow J/\psi \pi \pi p K$ | - $B^+ \rightarrow J/\psi \pi \pi K$ |
| - $\Lambda_b \rightarrow \chi_{c1} p K$ | - $B_s^0 \rightarrow J/\psi p \bar{p}$ |
| - $\Xi_b \rightarrow J/\psi \Lambda K$ | - $B_c \rightarrow J/\psi \pi \pi \pi$ |
| - $\Lambda_b \rightarrow \eta_c p K$ | - $B_c \rightarrow J/\psi 5\pi$ |
| - $\Lambda_b \rightarrow \Lambda_c p \bar{p} \pi$ | - ... |
| - $B^0 \rightarrow D^0 \bar{D}^0 K \pi$ | - ... |
| - $B^+ \rightarrow D^{(*)} \bar{D} K$ | |

and more coming soon

x10-50 increase in statistics will open a road for full amplitude analysis in these modes or sub-% sensitivity for narrow peaks



PRD 102 (2020) 051102

Unknown states

new frontiers

All-heavy tetraquarks

- See recent observation of structures in $J/\psi J/\psi$ spectra, most prominent at $m \sim 6900$, $\Gamma \sim 80$ MeV
minimal quark content is $[c\bar{c}c\bar{c}]$

- More states there? Spin-parity?
x-section vs. PT dependence?

statistics currently too low, will become accessible after Upgrade's x10-50 increase

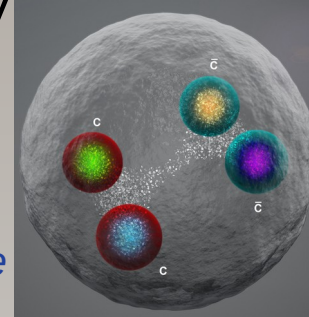
- Other decay channels?

- $J/\psi \chi_{c1}$, *expect $O(100)$ events after Upgrade given same $\sigma \times BR$*
- $J/\psi \eta_c$, *$O(10-100)$ events -"*
- $J/\psi J/\psi \pi\pi$, *$O(100-1000)$ events -"*
- $J/\psi J/\psi \gamma$, *$O(100)$ events -"*
- $J/\psi D\bar{D}$, *$O(100)$ events -"*
- $\Xi_{cc} \Xi_{cc}$, *rec. efficiency highly suppressed.*

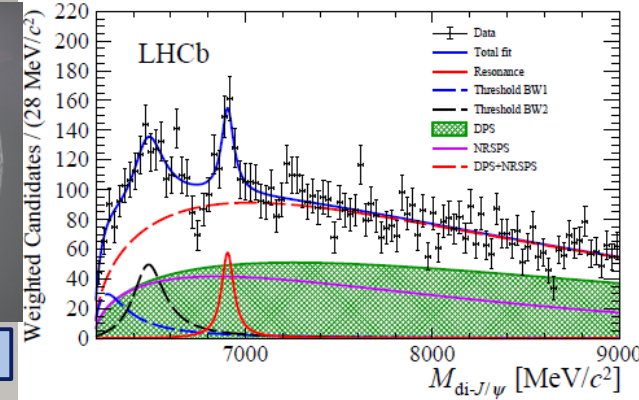
Won't be accessible unless few orders of magnitude difference in BR...

- Should there be equivalent $[b\bar{b}c\bar{c}]$ decaying to $Y(1S)J/\psi$
taking $\sigma(b\bar{b})/\sigma(c\bar{c}) \sim 0.1$ & $BR_{J/\psi/Y(1S)} \sim 2.5$ expect $O(100-1000)$ events after Upgrade's x10-50 statistics increase

even $[b\bar{b}b\bar{b}]$ tetraquark might be accessible after Upgrade II



LHCb-PAPER-2020-011



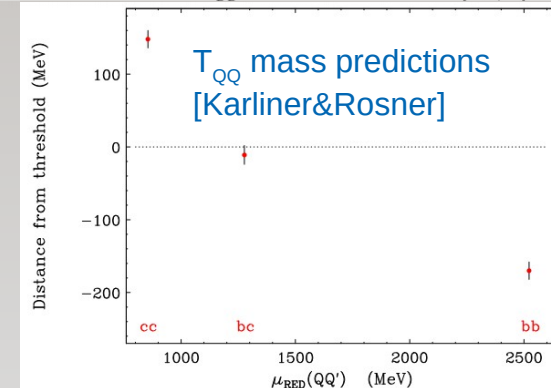
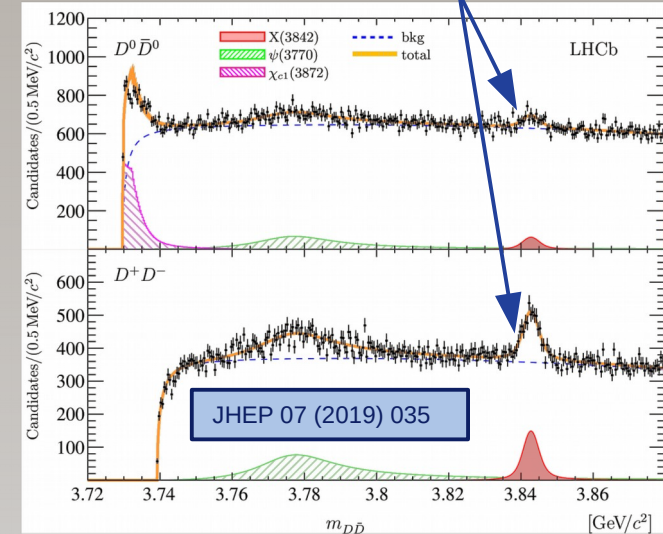
Other multiquarks

- Now having seen
 $[\bar{c}c\bar{q}q]$ – X(3872), $[\bar{c}c\bar{s}s]$ – X(4140), $[\bar{c}c\bar{u}d]$ – Z_c(4300)
 $[\bar{c}s\bar{u}d]$ – D⁺K⁻, $[\bar{c}cu]$ – Ξ_{cc}^{++} , $[\bar{c}ccc]$ – X(6900) in J/ψJ/ψ

can dream of more...

- Then, $[\bar{c}c\bar{u}d]$ – as tetraquark or DD* molecule, predicted to be within DD* threshold
 $[\text{Janc\&Rosina}], [\text{Karliner\&Rosner}], [\text{QCD Lattice}], \dots$
x-section comparable to that of Ξ_{cc}^{++} or X(6900)
 - should be seen as D⁰D⁰π⁺ or D⁰D⁺[γ/π⁰-missing] (recent X → DD̄ analysis as example)
 - molecular structure resembling X(3872), mutual analyses can fulfill the understanding
- Next $[\bar{c}c\bar{s}q]$, $[\bar{c}c\bar{s}s]$, or even $[\bar{c}c\bar{u}d\bar{q}]$, $[\bar{c}c\bar{u}d\bar{s}]$, $[\bar{c}c\bar{u}d\bar{u}d]$
 - via all DD, Λ_cD, Σ_cD, Λ_cΛ_c... combinations
- And potentially long-living $[\bar{b}c\bar{u}d]$, $[\bar{b}b\bar{u}d]$ via DD+h, B+h, BD+h, Ξ_{cc}^{++} +h, ...

discovery of X(3842)!



Other multiquarks

- And more... let's keep substituting a q with $[\overline{q}q]$ ($[\overline{u}d]$ with $J=0$ is lightest)
- With single heavy quark Q (b or c):
Pentaquarks $[\overline{Q}udud]$, $[Qudq\overline{s}]$ or Hexaquarks/dibaryon $[Qududq]$ ($Q = b$ or c)
if stable (tightly-bound or deuteron-like) will decay weakly

- with b -quark: if stable can decay to $J/\psi p/pp/d(?) + K/\pi\dots$ or $\Lambda_c p\pi$

first limit with Run1 data: $R(P_b/\Lambda_b) < \sim 10^{-3}$ [LHCb-PAPER-2017-043]

After upgrades can reach sensitivity in $R(P_b/\Lambda_b$ or H_b/Λ_b) around 10^{-4}

- with c -quark: to ppK , $ppK\pi$ or $\Lambda p\pi$, $dK\pi(?)$, *can reach $R(H_c/\Lambda_c) \sim 10^{-5}-10^{-6}?$*

- with s -quark: to $pp\pi$, $d\pi(?)$ *can reach $R(H_s/\Lambda) \sim 10^{-5}-10^{-6}?$*

compare to $\sigma(d)/\sigma(p) \sim 1.5 \times 10^{-3}$ in pp at 7 TeV [ALICE, arXiv: 1709.08522]

- If unstable \rightarrow promptly b/c -baryon + p combinations
(not many chances due to high prompt bkg)

- With two heavy quarks $[QQuudd]$

First predicted long time ago [Jaffe, PRL 38 (1977) 195] (*classic di-baryon*)

- more clear final state if unstable $\rightarrow \Lambda\Lambda$ or $\Lambda_c\Lambda_c$

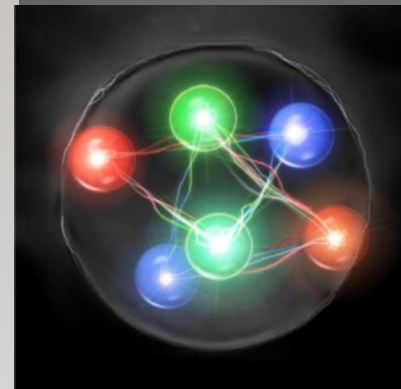
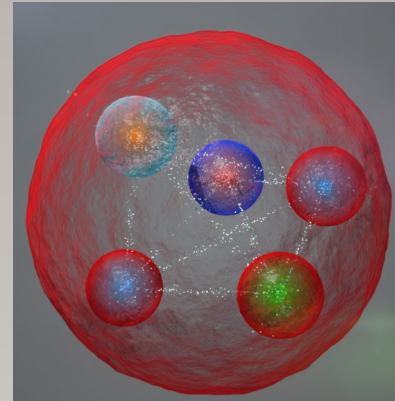
- if stable $[ccuudd]$: decay to $\Lambda_c\Lambda\pi$, $\Lambda_c pK\pi$, *can reach $R(H_{\Lambda_c\Lambda_c}/\Lambda_c) \sim 10^{-5}-10^{-6}?$*

- if stable $[ssuudd]$: decay to $\Lambda p\pi$, *can reach $R(H_{\Lambda\Lambda}/\Lambda) \sim 10^{-5}-10^{-6}?$*

compare to results by ALICE [arXiv:1506.07499]:

$dN/dy([sduudd]) < 4 \times 10^{-2}$ and $dN/dy([ssuudd]) < 6 \times 10^{-3}$, equiv to $R(H/\Lambda) \sim 2 \times 10^{-4} (?)$;

- We should think about extending the dibaryon searches to heavy quarks



Conventional double-heavy

- $\sim 300 \Xi_{cc}^{++}$ **[ccu]** candidates observed with $\sim 20\%$ of current data.
Thus can expect $O(100k)$ after Upgrades
- Search for Ξ_{cc}^+ **[ccd]** and Ω_{cc} **[ccs]** (already ongoing with Run1&2)
 Lifetimes $\sim 1/3$ of Ξ_{cc}^{++} give ~ 0.25 loss of efficiency.
 $\sigma(\Omega_{cc}^+)/\sigma(\Xi_{cc}^{++}) \sim 0.2$ expected.
Thus can expect $O(10k)$ of Ξ_{cc}^+ events and $O(1k)$ of Ω_{cc}^+ after Upgrades
- with these yields excited Ξ_{cc}^* may become accessible via $\Xi_{cc} + K/\pi!$
- For conventional Ξ_{bc} **[bcq]**, Ω_{bc} **[bcs]** (searches already ongoing with Run1&2)
 x-section can be estimated as $\sigma(\Xi_{bc})/\sigma(\Xi_{cc}) \sim 0.1$ or $\sigma(\Xi_{bc})/\sigma(B_c) \sim 0.2$
 and many modes for searches:
 - $J/\psi + \Xi_c/\Lambda_c/\Lambda_c K$ *can expect $O(100-1k)$ events ...*
 - $\Xi_{cc} \pi^-$ *can expect $O(100-1k)$ events ...*
 - $D\Lambda_c, D\Lambda_c, DDp, \dots$ *$O(100-1k)$ events*
 - c-decay: $B^0 p, \Xi_b \pi^+, \Lambda_b \pi^+$ *$O(100-1k)$ events*
 - Penguin topologies / W-exchange: $\Lambda_c K, \Xi_c \pi^-, \Lambda_c \pi^-, DpK, \dots$ *$O(100)$ events*

see arxiv:1808.08865
for more details

Conclusion

- LHCb Upgrade(s) will provide tons of material for Hadron Spectroscopy studies



- To complete the picture that started to emerge

- And a whole new pile of pieces to assemble a picture yet to be seen



Snowmass feedback

- We plan to include these ideas in a LHCb white paper which will cover all physics topics as a separate chapter
- We hope to benefit from interactions with theory colleagues during the Snowmass process, in particular in the context of drafting “Diquark structures in hadron spectroscopy” and “Hadron-Hadron spectroscopy” white papers
- We count on Snowmass proceedings recognizing unique opportunities LHCb upgrades offer in answering important questions in hadron spectroscopy, which together with the other opportunities in flavor physics at LHCb, calls for continued support for participation of American physicists in this experiment